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# STATUS OF SAFETY & ENVIRONMENTAL ACTIVITIES FOR INERTIAL FUSION ENERGY

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## ABSTRACT

*Over the past several years, significant progress has been made in the analysis of safety and environmental (S&E) issues for inertial fusion energy (IFE). Detailed safety assessments have been performed for the baseline power plant concepts, as well as for a conceptual target fabrication facility. Safety analysis results are helping to drive the agenda for experiments. A survey of the S&E characteristics—both radiological and chemical—of candidate target materials has been completed. Accident initiating events have been identified and incorporated into master logic diagrams, which will be essential to the detailed safety analyses that will be needed in the future. Studies of aerosol generation and transport will have important safety implications. A Monte Carlo-based uncertainty analysis procedure has been developed for use in neutron activation calculations. Finally, waste management issues are receiving increased attention and are deserving of further discussion.*

## I. SAFETY ASSESSMENTS

In recent years, safety assessments have been completed for the leading IFE power plant designs, as well as for the prototypical target fabrication facility. Following is a brief summary of the key findings for the SOMBRERO and HYLIFE-II IFE power plant designs. For SOMBRERO, a combined loss-of-coolant accident (LOCA) with a loss-of-vacuum accident (LOVA) scenario was analyzed. For HYLIFE-II, two analyses were completed: a LOCA/LOVA scenario as was analyzed for SOMBRERO and a loss-of-flow (LOFA) accident in conjunction with a LOVA. Finally, a safety assessment was completed for a prototypical target fabrication facility. The target fabrication effort was focused on estimating the tritium inventory and conceivable tritium and/or activated target material releases.

The results presented herein assume average weather conditions, as directed by the Fusion Safety Standards from the Department of Energy (DOE) [1-2]. Recently, however, DOE has issued guidance that directs analyses to consider conservative weather conditions for development of the emergency planning zone [3]. Since the desire is to avoid the need for a public evacuation plan, one must now show that the EPZ boundary lies within the power plant's site boundary. Therefore, one must now use conservative weather conditions in dose calculations for the 1 rem no-evacuation plan requirement.

In the following results, tritium is the dominant contributor to the off-site dose. Moving from average to conservative weather conditions makes approximately an order of magnitude difference in the tritium site boundary dose. Thus, one can multiply these results by ten to get an approximate value for the dose under conservative weather conditions.

### A. SOMBRERO Assessments

The baseline dry-wall IFE concept is SOMBRERO [4]. SOMBRERO, as originally envisioned, would use a carbon fiber composite (CFC) first wall and blanket. Safety assessments for

SOMBRERO, conducted with the CHEMCON and MELCOR codes, indicated that considerable oxidation of the carbon-based structures might occur under loss-of-vacuum accident scenarios [5-6]. Since CFCs are known to readily absorb tritium under neutron irradiation, oxidation of the structures would be a mechanism for release of large quantities of tritium during an accident. The oxidation rates used in CHEMCON, however, were measured under conditions dissimilar to those expected in SOMBRERO. Since SOMBRERO could take advantage of newer CFC technology, an exploratory safety test of CFC combustion was performed.

Idaho National Engineering and Environmental Laboratory (INEEL) carried out a chemical reactivity test on a state-of-the-art CFC, NB31, a high thermal conductivity, three-dimensional composite of carbon fibers and impregnated pyrocarbon particles [7]. Reaction rates were generated for CFC temperatures of 525, 600, 700, 800, 900 and 1,000°C, all with a $21^{v}/_{o}$ oxygen-argon flow rate of 100 sccm. The resulting reaction rates and activation energy compare well with the literature on carbon oxidation and burnoff. The experiment data plots clearly show the three expected reaction regimes: chemical kinetic control, in-pore diffusion of oxygen, and boundary layer diffusion. The regimes and reaction rate curve are shown in Figure 1. These experiment data focused on a lower temperature range than the previous work; present results were combined with past work to develop an integrated oxidation rate equation for each reaction regime.

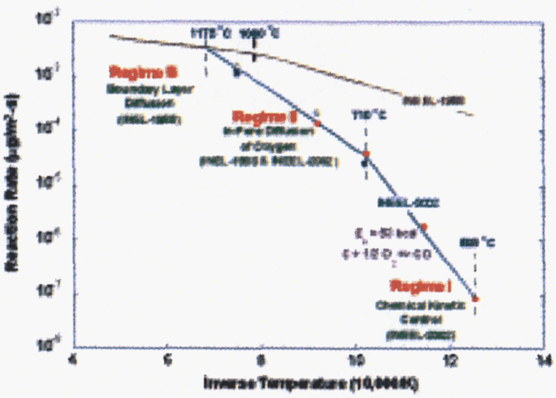

Figure 1. CFC-air reaction rate curve for INEEL-2002I, which is an integration of the INEL-1988 and INEEL-2002 chemical reactivity data.

The MELCOR thermal-hydraulics computer code used the integrated oxidation rate equation to analyze a SOMBRERO combined LOFA/LOVA As Figure 2 shows, use of the integrated oxidation curve produces higher FW temperatures due to CFC-air oxidation than were previously predicted. However, after about 10 hours, the FW CFC temperature falls below previous predictions and is considerably lower thereafter. The new oxidation curve suggests that the LOVA-induced CFC temperature transient is more manageable than previously predicted. The above is an excellent example of safety analysis and experimental work going hand-in-hand to determine what issues need to be addressed, addressing those issues, and producing a better overall result than what was previously available or possible.

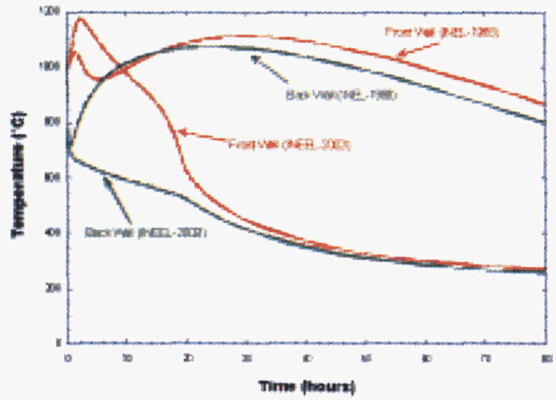

Figure 2. MELCOR prediction of SOMBRERO FW and back wall temperatures during a postulated LOVA/LOCA using INEL-1988 and INEEL-2002I.

Future work needs to study whether or not a relatively mild temperature excursion, without significant CFC oxidation, will release much, if any, of the tritium trapped in the FW/blanket. The level of tritium trapping also needs to be addressed—the recent work assumed an inventory of 1 kg of tritium, which is released in its more radiotoxic HTO form. Even without significant tritium releases, off-site doses will be excessive unless the chamber fill gas—xenon—is either treated on a continuous basis or is replaced with krypton or another less hazardous option. If tritium release can be averted, and the xenon is either scrubbed or replaced, then the off-site dose from a severe LOFA/LOVA in SOMBRERO can be limited to <4 mSv under average weather conditions—less than the goal of 10 mSv.

### B. HYLIFE-II Assessments

Safety assessments also have been completed for the HYLIFE-II thick-liquid power plant design; these include both a combined LOFA/LOVA, as was done for SOMBRERO, and a combined LOCA/LOVA scenario [8-9]. As in the SOMBRERO cases, tritium is the key safety issue. The earlier work suggests that only 140 g of tritium will be trapped in the stainless steel structure and piping [10]. This value has been assumed in the recent work, but it needs to be reaffirmed.

Heat transfer calculations, the results of which are given in Figure 3, show that the HYLIFE-II FW/blanket experience only a mild temperature excursion (several degrees) during a LOCA due to a relatively low decay heat from the stainless steel—an inherent advantage to a thick-liquid protection scheme. Still, TMAP (Tritium Migration Analysis Program) calculations indicate that any trapped tritium would rapidly be released (as HTO) during a LOCA/LOVA [11]. The off-site dose is dominated by the HTO release with stainless steel corrosion products and flibe making insignificant contributions (~10 μSv in each case). The total site boundary dose is 4.6 mSv for the LOCA/LOVA and 5.0 mSv for the loss of flow/LOVA scenario. Both assume average weather conditions.

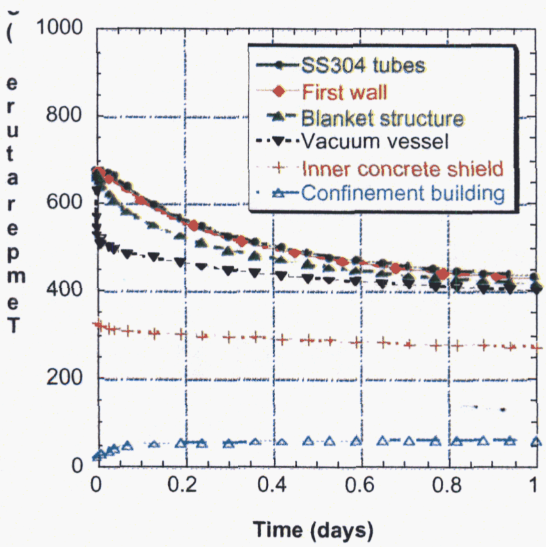


Figure 3. Shielding provided by the thick-liquid protection limits neutron activation to sufficiently low levels that the HYLIFE-II first wall can passively handle its radioactive decay heat, even during a loss-of-coolant accident.

### C. Target Fabrication Assessments

A preliminary assessment has been completed for a baseline target fabrication facility [12]. The key conclusion, for indirect-drive targets, is the need to perform assembly at cryogenic temperatures only after the capsules have been filled with DT. Filling targets after the capsules have been assembled inside hohlraums would lead to tritium inventories (in the target fabrication facility) that are 14-32_ larger than those for cold-assembled targets. Direct-drive targets, especially those with thin plastic ablators, need to be manufactured from materials with a high DT solubility to avert an exceedingly large tritium inventory [13]. Recent work demonstrates the considerable gains that have been made in this area [14].

The physics of DT combustion in air and the hazards associated with the use of high-pressure gas are discussed in ref. 15. It is noted that isotopic effects are important for hydrogen, and thus, use of the protium approximation (as opposed to deuterium and tritium) is overly conservative when considering D-T deflagration events for large volume rooms.

### D. Chemical Hazards

Traditionally, accident assessments have focused on estimation of radiological doses to the public due to potential releases of activated materials during off-normal events. However, the use of toxic (chemically hazardous) materials in some conceptual designs poses the additional hazard of chemical exposure from an accident perspective. Examples include fluorine in the case of KrF-driven IFE power plants, and some hohlraum material candidates for indirect-drive IFE concepts.

Recently, we performed an assessment of the chemical toxicity of mercury and lead as potential target materials [16]. Results show that release rates of the order of 100 mg/s would reach the maximum allowed concentration for public protection at the site boundary. Also, a direct comparison between the radiological and toxicological hazards of these two materials was presented. A new and interesting finding was that concentrations that would yield an acceptable radiological dose would exceed the chemical safety requirements. The results from this study demonstrate that chemical hazards must also be considered to provide a complete safety assessment for fusion power plants.

## II. PROBABILISTIC RISK ASSESSMENT

An effort to use Probabilistic Risk Assessment (PRA) in IFE safety assessment and design safety support has begun. One of the initial PRA steps is to define the set of plant off-normal events or accidents that will be analyzed. This PRA step is called accident-initiating event identification. The initiating events (IEs) are the "accident starters" that can result in off-site consequences. Completeness at this stage is essential; the results of IE identification will affect the rest of the PRA. Therefore, analysts use multiple means to identify the IEs. A preliminary IE identification and compilation task [17-18] has been performed under the ARIES-IFE program. The IE identification task has listed potential events for two IFE power plant designs, SOMBRERO and HYLIFE-II. These two conceptual designs were chosen since they represent opposite approaches to IFE power plants; SOMBRERO is a dry wall design with direct laser drive and HYLIFE-II is a wet wall design with indirect ion beam drive. Several IE identification methods were used, including preliminary hazards analysis, historical safety document review, review of operating experiences from existing facilities, and a master logic diagram of each of the two conceptual designs. The results of this task are too lengthy to present here. In summary, the two lists of potential IEs contain the expected events that challenge most types of thermal power plants (e.g., loss of coolant accident, loss of heat sink, loss of offsite power, etc.). Many of the events are initiators simply due to the challenge of the event to safely handle some type of energy flow or hazardous material.

Some general fusion plant potential IEs are loss of vacuum accident (LOVA) and blanket fault events. Some of the IEs that are unique to fusion and/or tritium handling are tritium cleanup faults and loss of tritium confinement. The SOMBRERO design has some design-specific initiators: building breach, building gas circulation system breach, and laser faults – including loss of KrF lasing gas. HYLIFE-II also has some design-specific events associated with the heavy ion beam accelerator, including LOVA in the reactor or an ion beam line, ion beam steering magnet faults, and dry spot formation in the wet wall system.

A compiled list of preliminary IEs is the initial point of IE analysis. These two lists would be refined by more detailed analysis as the two designs mature. Further IE analysis steps would be to prioritize the preliminary list of initiating events by severity and expected offsite consequences. Then each list can be reduced to contain only those events that offer unique consequences and require individualized analysis.

## III. AEROSOL GENERATION & TRANSPORT

The explosion of a high-yield target in an economically attractive IFE reactor may remove material from surrounding walls and/or protective surfaces. This material must be recovered or removed from the system prior to the next shot. Various schemes have been developed to protect internal reactor structures- thick liquid walls or large flowing sheets, solid walls with a thin, continuously refreshed liquid surface, and solid walls protected by heavy gas backfilled into the chamber are promising concepts. For each of these concepts, intense energy deposition on exposed surfaces potentially leads to aerosol formation. As evaporated material expands and cools, in-flight condensation may occur away from the wall, and particulate may be produced at the wall by mechanisms such as explosive boiling or melt-layer ejection. Aerosols in the post-shot IFE chamber are beneficial in that particulate material greatly enhance the total surface area available for condensation of residual vapor. However, should a significant concentration of aerosol remain in the chamber during initiation of the next shot, deleterious effects may be encountered as driver beams and the target propagate through the chamber.

To better understand their impact, a series of studies has been performed that predicts the behavior of aerosol in IFE chamber systems [19]. The underlying mechanisms responsible for aerosol formation, growth, and movement that are considered in the present model include homogeneous nucleation, condensational growth, agglomeration, and convective transport. Other mechanisms unique to the IFE chamber are being considered for future addition to the model. Analysis of dry-wall and wetted-wall protection schemes demonstrate that aerosol is dispersed throughout a spherical chamber at the time of the next shot. For example, a wall protected with liquid flibe generates aerosol with an average mass concentration of ~10 mg/m$^3$ in a chamber with a radius of 6.5 m exposed to the energy flux from an in-direct drive, 458 MJ target. Figure 3 shows the resulting aerosol size distribution in the central region of the chamber. At 250 ms after the shot, the aerosol concentration is ~10$^9$ particles/m$^3$ for 1 μm particles.

Scoping studies such as this indicate aerosol populations may indeed persist in an IFE chamber, hence provisions for clearing particulate from the chamber should be considered. Further development of aerosol models in IFE systems will include techniques for evaluation of the effectiveness of proposed removal schemes.

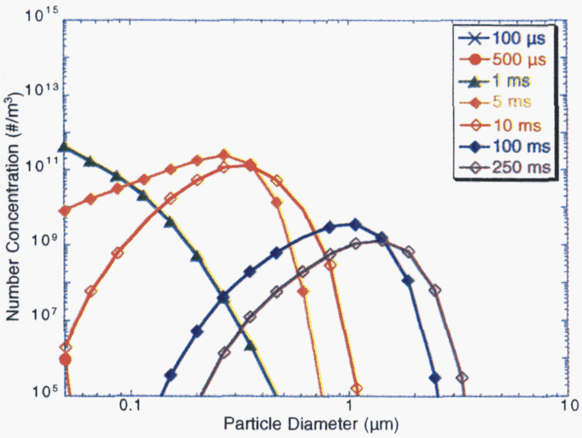


Figure 3. The particle size distribution of flibe droplets changes in time as particles grow due to condensation and agglomeration. Particles initially form from wall material evaporated by exposure to the x-ray and ion flux.

## IV. UNCERTAINTY ANALYSIS

A Monte Carlo uncertainty analysis procedure for activation calculations has been developed based on simultaneous random sampling of all the cross sections involved in a problem, and it has been implemented in the activation code ACAB [20]. Using the procedure, it is possible to propagate activation cross section uncertainties forward to provide uncertainties on the overall radionuclide activities and any activity-based radiological results. By considering all cross sections simultaneously, it is possible to consider multiple reaction pathways, which are likely to have different levels of uncertainty associated with them but may all make significant contributions to the overall result. Ultimately, this capability will be used to identify nuclear reactions that are both important to the desired results and have relatively large uncertainties. It is hoped that this will help drive experiments to make a more precise determination of key activation cross sections.

## V. WASTE MANAGEMENT

In much of the previous work (in both magnetic and inertial fusion studies), great effort has been expended in an attempt to avoid the generation of high-level waste. Relatively little effort has gone into reduction in the overall waste stream. Clearly, the public is able to understand the concept of waste volume. It is not clear, however, that the public understands about the differences between waste that meets Class C requirements versus waste that does not meet these requirements [21-22]. As a result, the choice between generation of small quantities of high-level waste versus large quantities of low-level waste is a difficult one worthy of community discussion and debate.

Clearly, this discussion must include issues such as clearance, recycling/reuse, and disposal. The political aspects, however, cannot be ignored. Now is the time for the community to engage in such discussions. Following are two IFE-specific examples of sub-systems that might benefit from such a discussion.

### A. Magnet Shielding

The shielding and activation of the final focusing magnets for many-beam heavy-ion fusion (HIF) systems has been studied over the past several years. Considerable improvements have been realized as the radiation transport models have become more detailed and more accurate. The first generation of modern shielding designs resulted in magnets that might only survive for ~1 year and would produce waste that would be above Class C. The most recent analyses, however, completed for the HIF Robust Point Design, indicate that magnet lifetimes in excess of the power plant lifetime are possible and that only a minor extrapolation will yield magnet designs that generate only low-level wastes [23].

In order to protect the final focusing magnets, inner (and outer) bore shielding of at least 5 cm is required. Additionally, the entire magnet array needs to be placed within a large shielding structure, and large frontal shielding is required. A study to determine the minimum system waste is needed.

### B. Target Materials Selection

We have studied the selection of target materials for use in indirectly-driven IFE [12, 24]. In addition to limiting potential off-site doses during an accident, it is highly desirable to enable recycling of the target material: for a fusion power of 2240 MW and a target yield of 350 MJ, the throughput of high-Z target could be as high as 120 tons/year (3600 tons over the plant lifetime). If target material could be recycled on a weekly basis, the mass could be reduced to ~2 tons over the plant lifetime.

The main constraints in recycling target materials are activation and the resulting dose rates experienced by the target fabrication equipment and/or workers. Additionally, recycled target materials may eventually become activated to the point where they would no longer be classified as low-level radioactive waste. Is it better to generate large quantities of low-level waste or to allow some small quantity of waste that does not meet Class C requirements?

## VI. SUMMARY AND FUTURE WORK

During the past several years, considerable progress has been made in advancing our understanding of safety and environmental issues in inertial fusion energy. Safety assessments have been completed for the leading power plant concepts, as well as for a prototypical target fabrication facility. Probabilistic risk assessment activities have begun with identification of potential accident initiators. This will set the stage for more detailed accident analyses. Aerosol generation and transport is being studied for IFE. Aerosols potentially have important implications both for accident analysis and baseline operations (e.g., chamber clearing and beamline contamination).

Despite the recent progress, there is still much work to be done. While safety assessments are valuable, they differ from full safety analyses. The latter, however, requires both more detail in the designs and more data from experiments. This detail will be developed over the next few years as the designs are updated and, perhaps, a new design study is completed.

Finally, waste management issues are an active area of study. The community could benefit from more discussions and debate on this topic. A main discussion point should be whether or not generation of *any* amount of above Class C waste is tolerable.

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